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Exposure of inshore corals to suspended sediments due to wave-resuspension and river plumes in the central Great Barrier Reef: A reappraisal

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ABSTRACT

Suspended sediment in the coastal zone is an important limiting factor for the growth and health of inshore coral reefs. The Great Barrier Reef (GBR) lagoon receives sediment from a number of tropical rivers and the physical and biological effects of riverine discharge and turbidity within the lagoon are of considerable scientific and public interest. Published data from two inshore regions of the GBR are reviewed herein to evaluate the relative influence of river plumes and wave resuspension on suspended sediment concentration (SSC) around coral communities over a range of timescales. Data from Cleveland Bay and from other sites near the mouth of the Tully River show that wave resuspension is the most dominant mechanism controlling SSC at inshore reefs. At many nearshore areas today fine-grained bed sediment is abundant, consistent with millennial-scale geological evidence of sediment dispersal prior to European settlement and catchment impacts. Flocculation, particle settling and dilution occurs within the river plume, and riverine sediment concentrations at reefs directly attributable to individual flood inputs is significantly reduced, suggesting that the plume component is a relatively small contribution to the total suspended sediment mass balance over inter-annual timescales. Resuspension events can generate higher ambient SSC than that measured in flood waters (e.g. Tully River). In addition, while visually spectacular, satellite and aerial images offer limited quantitative information of total sediment load carried by hypopycnal plumes, as many of these plumes may contain algal blooms but relatively low concentrations of suspended sediment (ca. <5 mg/l). Nonetheless, the cumulative effect of sediment-laden plumes may be a vector for other adsorbed contaminants of potential ecological concern, but coral smothering by hypopycnal plumes alone appears an unlikely impact particularly at inner- and middle-shelf reefs exposed to high wave energy and resuspension. Terrigenous sediment dispersal and turbidity within the GBR is governed by physical processes common to many continental shelves globally. Despite the examples examined in detail herein, the role of frequency, magnitude and duration in determining the impact or exposure of corals to elevated SSCs is poorly constrained by limited quantitative measurements during events, and our ability to place these into a broader temporal context. More high-quality observational data, at meaningful length-scales, can only enhance our ability to disentangle potential behavioural shifts in environmental responses.

1. Introduction

Considerable scientific and societal debate surrounds the scale and significance of anthropogenic activities impacting the Great Barrier Reef (GBR), particularly the quantification of sediment runoff, and the effects of nutrients and pesticides from agriculture. Some studies have argued that the GBR is already seriously degraded from a pristine state (Pandolfi et al., 2003; Wolanski et al., 2003; Hoegh-Guldberg, 1999). Similarly, the Scientific Consensus Statement on Water Quality in the GBR (State Government of Queensland (2008)) alludes to the well-established increases in sediment and river-borne discharges to the GBR lagoon (e.g. McKergow et al. (2005)), and implies a significant impact on water quality from river plumes and likely changes in the sedimentary environment and ambient water quality close to inshore reefs.

Aside from debate around the magnitude of impacts, there is strong field and laboratory evidence that high suspended sediment

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concentrations (SSC) and sediment settling can cause coral mortality by reducing light or smothering (Anthony and Fabricius, 2000; Fabricius and Wolanski, 2000). In addition to these direct effects, sediment-laden flood waters can also carry nutrients and contaminants into coastal waters, which may be desorbed into the water column. For these reasons, increased riverine inputs and hypopycnal flood plumes have been argued as a significant threat to the reef (e.g. Wolanski and Spagnol (2000), Devlin et al. (2001a), Lambrechts et al. (2010), Wolanski et al. (2008), De'ath and Fabricius (2010)).

Along the North Queensland coast, floods are usually generated by the passage of a monsoonal event or tropical depression, accompanied by a period of high wind and significantly elevated sea-states and atypical bottom currents. Hence, particularly energetic bed resuspension and transport events on the GBR shelf can occur simultaneously with torrential rainfalls and flood plumes (e.g. Gagan et al. (1990), Larcombe and Carter (2004), Carter et al. (2009)). Despite the strength of this causal link, field data of the widespread impact on reefs directly attributable to terrestrial delivery events are scarce and inconclusive, and as we explore further herein, with considerable uncertainty surrounding the coherence of flood and turbidity maxima. Moreover, evidence is ambiguous whether the last century of anthropogenically increased riverine sediment supply (e.g. McKergow et al. (2005)) is having a quantifiable long-term impact on the growth and biodiversity of significant portions of the reef. The aim of this paper is to utilise water quality measurements and findings published over the last decade to reappraise the link between river plumes and SSC on the reefs of the central GBR. From this perspective we offer a synthesis and discussion of current knowledge, guided by thematic lines of enquiry to re-analyse published work regarding sediment hydrodynamics, water quality and the potential magnitude of anthropogenic contributions.

2. Physical hydrodynamic and sedimentological setting of the central Great Barrier Reef

This study is primarily focussed on the central section of the GBR lagoon that spans the climatically diverse regions of the southern dry-topics and extends into the northern wet-tropics. A feature of the dry-topics is the strong seasonality in rainfall. For example, in the Townsville region approximately 80% of the average annual rainfall of 1114 mm occurs in the summer wet season months of December–March (Bureau of Meteorology, 1998). Southeast trade winds dominate for the dry-season months of April–November, creating significant coastal turbidity and generating a northwestward longshore movement of inner shelf waters and suspended sediment (Belperio, 1978; Walker, 1981; Wolanski and Ruddick, 1981; Lou and Ridd, 1997). Wind speeds weaken and become more variable during the summer wet season, coinciding with the highest levels of cyclone activity (Bureau of Meteorology, 1998). The predominant wave climate comprises locally generated, short period (<6 s) wind waves, and longer period (>7 s) swell waves that are generally oriented from the east–southeast with the prevailing wind direction (King, 1994; Patterson, 1994; Larcombe et al., 1995; Lou and Ridd, 1996; Orpin et al., 1999).

Maxwell (1968) first described and mapped the broad-scale pattern of mixed siliciclastic and carbonate sedimentation for the length of the GBR lagoon. In the central GBR the continental shelf is approximately 100–150 km wide and the shelf break is around 80 m deep. Belperio (1983) recognised three distinct zones of shelf sedimentation: terrigenous (inner shelf), palimpsest (middle shelf), and reefal (outer shelf), with these zones broadly corresponding to water depths of ~0–20 m, 20–40 m, and 40–80 m, respectively. Today, transport and resuspension processes have led to the development of a strongly sediment-partitioned shelf, with modern riverine sediment adjacent to the coastline and biogenic carbonates on the middle and outer shelf (e.g. Orpin et al., 2004a). At the coast, riverine deposits of post-glacial mud form a shore-attached, seaward- and laterally (westward) thinning sediment wedge that can extend out to the 20 m isobath. A northward littoral sand drift system, driven by the prevailing southeasterly trade winds, extends north from the mouth of the largest rivers (e.g. Burdekin River) and entrains the siliciclastic sand-sized bedload output to form spits and bars (Belperio, 1978; Hopley, 1982). Except in protected embayments, Holocene mud deposits on the inner shelf are generally thin (<2.5 m), and in many areas of the middle shelf a pre-Holocene surface crops out on the sea floor (e.g. Johnson and Searle (1984), Orpin et al. (2004a)).

Stratigraphic analysis by Fielding et al. (2006) suggested that the Burdekin Delta has retained the majority of the total Holocene sediment mass delivered by the river, rather than being dispersed into the lagoon. Today, shelf dispersal and hypopycnal plumes from the Burdekin River occur only during floods when flows exceed $\sim 2000\ m^3/s$ (Belperio, 1983). Unlike the present day, during the latter stages of the last-glacial shoreline transgression in the early Holocene rivers discharged sediment to the middle shelf. With ongoing sea-level rise this material was subsequently redeposited around offshore islands like the Whitsunday Island group, which served as an efficient sediment trap for northward littoral transport. Both the availability and volume of bedload material surpassed modern riverine sediment supply (Heap et al., 2002).

Along the length of the inner and middle shelf of the central GBR, numerous bedrock islands (e.g. Magnetic, Family, and Whitsunday islands) host a diverse range of fringing reef and reef flat coral communities, including both soft and hard coral species. Field studies in the 1980s and 1990s suggested that many inshore areas close to fringing and inner-shelf reefs contained considerable thicknesses of fine-grained deposits (e.g. Johnson and Searle (1984), Larcombe and Carter (1998)). Based on these associations and limited hydrodynamic observations, Woolfe and Larcombe (1998) first proposed that high SSC events on the inner shelf were not sediment-supply limited, but instead elevated SSCs were controlled by the energetics of wave-driven seabed resuspension.

Many authors over recent decades have highlighted the difference in sediment and nutrient delivery for dry- versus wet-tropics rivers, and the estimated potential impacts of land-use change (e.g. Moss et al. (1992), Furnas et al. (1996), Neil et al. (2002), Furnas (2003), McKergow et al. (2005)). From an appreciation of the offshore patterns of terrigenous sediment accumulation, these regional differences in dispersal persisted throughout the Holocene (e.g. Searle and Hegarty (1982), Johnson et al. (1986), Carter et al. (1993), Woolfe et al. (1998), Larcombe and Carter (2004), Bostock et al. (2007)) resulting in mud deposits several metres thick (e.g. Marshall (1977), Belperio (1983), Johnson and Searle (1984), Brunskill et al. (2002), Pfitzner et al. (2004), Orpin et al. (2004a), Bostock et al. (2006a,b), Fielding et al. (2006)). Throughout the Quaternary life cycles of the GBR with glacio-eustatic changes in sea level, it is also well established that carbonate production and early reef initiation occurred during periods of high coastal turbidity, maintained by sediment supply and oceanographic processes (Harris et al., 1990; Peerdeman and Davies, 1993; Dunbar et al., 2000; Dunbar and Dickens, 2003; Page et al., 2003). Over geological timescales, reef development and water quality are inextricably linked.

To maintain high SSCs in the water column requires energetic water motions and a ready and constant supply of mud (Wright, 1995). Accordingly, sediment availability is central to the argument of Woolfe and Larcombe (1998) and Larcombe and Woolfe (1999a,b). The majority of the washload sediment discharged from rivers along the coastline of the GBR is efficiently trapped in shallow (<20 m), northward-facing embayments such as Bowling Green, Cleveland, Missionary, Trinity and Princess Charlotte bays, sheltered from the southeasterly trade winds (Belperio, 1983; Larcombe and Woolfe, 1999a,b; Lambeck and Woolfe, 2000; Woolfe et al., 2000; Orpin et al., 2004b). Here, accumulation rates at depocentres can reach >1 cm/y in shallow quiescent sites adjacent to mangrove-forest margins (Brunskill et al., 2002) and sheltered behind lee-headlands (e.g. Carter et al. (1993), Orpin et al. (2004a)). Brunskill et al. (2002) suggested that most estuarine fine-grained, organic matter-rich sediment is sequestered into temporary (century to millennial scale) storage sites until filled to some equilibrium surface, and deposition ceases and new accumulation sites are created. While the post-European increase in riverine supply contributes to the overall sediment budget, Woolfe and Larcombe (1998) inferred that the underpinning sedimentary hydrodynamics at inner-shelf reefs is not supply limited; the implicit assumption being that water quality has remained largely unaffected.

Despite the undoubted role and efficiency of the embayments, deltas and coastal islands in trapping sediment, there is evidence for a small, but measureable and persistent flux of terrigenous sediment across the continental margin operating over geological timescales. Dunbar et al. (2000), Dunbar and Dickens (2003), Francis et al. (2007) and Bostock et al. (2009) document the glacio-eustatically-controlled flux of sediment across the shelf over the last 300 ky using sediment cores taken from the Queensland Trough and slope, and the Capricorn Trough. The most rapid rates of sediment accumulation in the Queensland Trough occur during periods of rapid sea-level rise and shoreline transgression when wave-driven coastal erosion generated large quantities of sediment that were transported along and across the shelf. However, significant terrigenous sedimentation has been measured in the Queensland Trough since the mid-Holocene sea-level highstand. There are a variety of mechanisms that might be responsible for fluxes of sediment seawards of the coastal zone, including river plumes, diffusion, nepheloid layers, resuspension and flows during cyclones, and near-bed return flows caused by onshore winds (Gagan et al., 1990; Wolanski, 1994; Orpin et al., 1999; Wolanski and Spagnol, 2000; Larcombe and Carter, 2004; Carter et al. 2009; Webster and Ford, 2010).

3. Method and data sources

The analysis first proposed by Woolfe and Larcombe (1998) can now be revisited and critically assessed subsequent to a decade of new field data from the inner-shelf region of the GBR. Here, we analyse recent advances that contribute to the understanding of coastal sediment transport processes and geological history of fringing reefs. Two well-studied areas provide the focus for discussion (Fig. 1): (i) Magnetic Island and Cleveland Bay, which are down-current of the influence of river plumes from the large Burdekin River in the dry tropics; and, (ii) fringing reef systems offshore from the mouth of the Tully River. The Tully River drains one of the wettest areas of the North Queensland coast and discharges into a section of the lagoon where numerous fringing reefs and islands are located. The Family Isles are 10–15 km from the river mouth and there is a small coral shoal at Lugger Bay 10 km to the north of the Tully River mouth. Collectively, these data will allow better deconvolution of the balance between SSC from river discharge and that contributed from wave-generated resuspension. Moreover, the synchronicity of these two contributions will be explored in detail. Table 1 summarises the literature sources that are discussed and re-analysed herein.

4. Re-analysis

This section provides a synthesis and reappraisal gleaned from recently published studies. Lines of enquiry are articulated under a series of sub-headings that reinforce key concepts relevant to a broader understanding of suspended sediment behaviour at reef environments.

4.1. Coastal hydrodynamic control on ambient SSC and sediment transport

Some inshore-coral reefs show evidence of relatively high SSC over geological timescales: an environmental factor supported by the initiation and growth history of corals. Pioneering studies by Johnson (1985), and Johnson and Risk (1987), and more recently by Smithers et al. (2006), showed that some fringing reefs, bathed in turbid coastal water, were initiated on a muddy substrate that would readily be resuspended by wave motions. Smithers et al. (2006) found that many reefs go through long periods (millennia) of sustained slow growth in conditions often considered poor for reef establishment, but are now covered in a veneer of well-developed coral communities.

Larcombe and Woolfe (1999a,b) and Larcombe et al. (2001) showed that a combination of energetic oscillatory-wave motions and an abundance of fine-grained terrigenous material around reefs ensured high SSC events at Paluma Shoals (Table 1). The dynamic nature of fringe-reef turbidity is important also. At Paluma Shoals, turbidity of >40 NTU probably occurs for a total of >40 days each year, and relatively little time is spent at intermediate turbidities (15–50 NTU) (Larcombe et al., 2001). Extended time spent at either low or high turbidities is consistent with the biological behaviour of some species of corals to adopt two alternative mechanisms of functioning (autotrophy and heterotrophy) in response to different levels of turbidity (Anthony and Fabricius, 2000), and the periodicity of these turbidity cycles will critically affect the energetics of benthic primary producers (Anthony et al., 2004). Similarly, water turbidity data from fringing reefs around Magnetic Island show a strong correlation between wave climate and resuspension (Larcombe et al., 1995; Orpin et al., 2004b; Anthony et al., 2004). Orpin et al. (2004a) present data from Geoffrey and Nelly Bay of high water turbidity during an unseasonal storm with extremely energetic waves. Water turbidities exceeded 100 NTU at a number of sites during the event and were significantly elevated (above 10 NTU) for around a week. Larcombe et al. (1995) also showed periods of significantly elevated SSC during large wave events, including very high SSC (over 200 mg/l) within Cleveland Bay immediately adjacent to Magnetic Island (Fig. 1). Moreover, a sediment hydrodynamic analysis using a 22-year wave-climate record by Orpin et al. (1999) suggests that high-energy wind-waves exist for approximately 40 days/yr in the Townsville region, which are capable of resuspending bed sediment in water depths to around 15 m. This general hydrodynamic behaviour is not limited to the dry-tropics, albeit that the wet-tropics of the Cairns region tends to be significantly less energetic (Orpin et al., 1999). For example, Wolanski and Spagnol (2000) noted that during the dry season, when riverine sediment inflow was negligible, the material making waters turbid in the coastal zone off the Cairns region was terrigenous mud, resuspended by wind-generated waves. Other near-bed effects were inferred further offshore during a calm period.

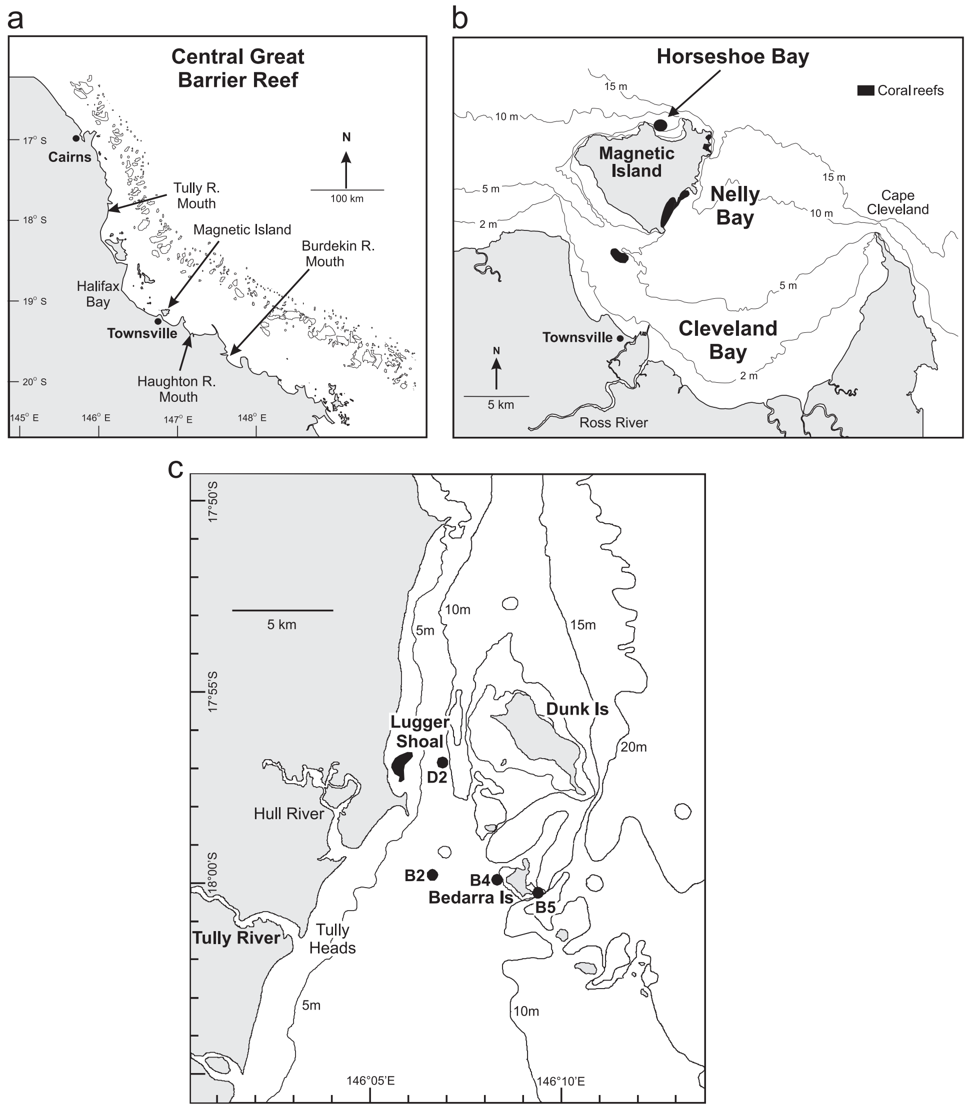

Fig. 1. (a) Central GBR region and detailed maps of (b) Magnetic Island in Cleveland Bay and (c) the Family Islands group off the mouth of the Tully River.

These empirical field measurements suggest that high SSC events, on the inner shelf at least, were not sediment-supply limited, but instead are controlled by the energetics of wave-driven resuspension of the muddy seabed. The corollary of this hypothesis is that any realistic increase, or decrease, to riverine sediment supply to the muddy coastal zone is likely to be overwhelmed by resuspension as the dominant environmental driver for elevated SSC (Larcombe and Woolfe, 1999a). In this light, perhaps the more compelling question is what time period might be required for the inner-shelf sedimentary system to become supply limited?

Irrespective of the debate around sediment supply, the role of waves controlling ambient SSC at coastal reefs was not considered in the Scientific Consensus Statement on water quality in the GBR (State Government of Queensland, 2008) or in the most recent Great Barrier Reef Outlook Report (Great Barrier Reef Marine Park Authority, 2009), despite its well-established relationship with oceanographic forcing. Similarly, the link between agricultural run-off and potentially deleterious effects on the GBR have been implicated in some studies (e.g. De'ath and Fabricius (2010), Kroon et al. (2012)) with limited consideration of the sediment hydrodynamic or geological context.

4.2. *Geological evidence for sustained sedimentological or coral-community change directly attributable to anthropogenic activities*

Differentiating environmental shifts at reefs from the background sedimentary setting is a difficult task but some information already exists (e.g. Larcombe and Woolfe (1999b), Perry et al. (2009) Perry et al. (2008, 2011) Perry and Smithers (2011)). Many of the inshore shoals are very young. For example Perry et al. (2009) found that Lugger Bay shoal is <1000 years old. Perry et al. (2008) studied a similar, highly turbid reef at Paluma Shoals and found that the coral assemblages exhibit no measurable evidence of community shifts attributable to post-European water-quality changes, perhaps 20% of the reefs life's history. Hence, at these reef sites health and growth has fluctuated through cycles independent of anthropogenic forcing. Perry and Smithers (2011) recognised several major changes in coral reef growth rates over the last 8500 years, but cautioned that "degraded reef states cannot *de facto* be considered to automatically reflect increased anthropogenic stress".

McCulloch et al. (2003) used Ba/Ca ratios from coral cores from Pandora and Havannah reefs on the inner shelf of Halifax Bay to infer changes in sediment delivery to the GBR from the Burdekin River around 140 km to the south. Large annual peaks in the coral

Table 1
Summary of findings and interpretations from listed recent publications and data sources.

Theme	Recent information source	Data type	Summary of reinterpretations from current study
Regional coastal hydrodynamics and sediment transport	Brunskill et al. (2002), Cooper et al. (2008), Dunbar and Dickens (2003), Dunbar et al. (2000), Francis et al. (2007), Larcombe et al. (2001) Orpin et al. (1999), Orpin et al. (2004a,b), Wolanski and Spagnol (2000), Wolanski et al. (2008)	Wave and turbidity data Cores, sediment composition and grain size Wave and turbidity data	• Hydrodynamics largely control SSC and sediment transport • Northward-facing embayments trap most sediment • Near-bed transport ephemeral beyond the coastal zone • Significant cross shelf sediment transport to the Coral Sea measurable over geological timescales
Geological evidence of environmental change over the Holocene and Anthropocene	McCulloch et al. (2003), Perry and Smithers (2011), Perry et al. (2008, 2009, 2011), Smithers et al. (2006)	Cores, sediment composition and grain size Coral cores	• Confirmation of Larcombe and Woolfe hypotheses (not sediment-supply limited) • No evidence of change in nearshore coral communities • Ba/Ca ratios may be indicative of riverine sediment discharge but not of SSC at coral
Cleveland Bay and Burdekin River floods	Cooper et al. (2008), Devlin et al. (2001), Lambrechts et al. (2010)	Wave and turbidity data River discharge data Satellite images Plume characteristics	• River plumes are minor direct contributors to SSC events in Cleveland Bay • Wave-driven resuspension dominates mass balance of SSC inshore • Most sediment falls from suspension well before reaching Magnetic Island • Satellite images can give an ambiguous impression of SSC in hypopycnal river plumes
The Family Islands and Tully River floods	Devlin et al. (2001), Devlin and Schaffelke (2009), Wolanski et al. (2008)	Wave and turbidity data River discharge data Plume characteristics	• River plumes are minor direct contributors to SSC events near fringing reefs over short timescales • Wave-driven resuspension dominates mass balance of SSC • Nearshore SSC is sometimes higher than in the Tully River flood water • Tully River is a minor contributor to sediment fluxes in the region

calcium carbonate Ba/Ca ratio were synchronous with high river discharge peaks and were interpreted as a measure of the sediment load of the Burdekin. Moreover, Ba/Ca ratios since 1860 appear to have gradually increased, indicating that the sediment discharged by rivers has increased by a factor of perhaps 5–10 since settlement due to the introduction of grazing and intensive agriculture. However, this approach ignores the potential influence of resuspension of abundant quantities of sediment already deposited on the inner shelf, and as such their geochemical record may not be a proxy for total suspended sediment at reef sites as they infer. Subsequent discussions have appeared in the literature surrounding causal links of reef impacts that now includes possible misinterpretations of the findings of McCulloch et al. (2003) For example Cole (2003) interprets that the results show "sedimentation on the reef increased dramatically following European settlement and agricultural expansion in northeast Australia". More correctly, eroded barium transported by the river offshore is not necessarily fixed to sediment particles. Instead, it becomes a dissolved tracer or is incorporated with organic material (McCulloch et al., 2003). Indeed the Ba/Ca peaks shown in McCulloch et al. (2003) were single, sharp asymmetric annual peaks occurring at the beginning of the year, which subsequently decay gently to background levels with a time scale of a few months. The shape of the Ba/Ca peaks should be contrasted with the highly irregular turbidity time series of Cooper et al. (2008) (Fig. 2) that shows high frequency turbidity fluctuations at time scales of hours to weeks, and no period of the year where turbidity is consistently high or low.

One counter argument to such a proposition is that sediment quality within the lagoon has changed subsequent to European settlement (last century), particularly within southern and central Queensland catchments. Suspended sediment yields for large dry-topics catchments with extensive grazing lands, like the Burdekin, Herbert and Fitzroy rivers, have experienced a 4–6-fold increase above modelled natural yields (e.g. Neil et al. (2002), McKergow et al. (2005)). To date, sedimentological and geochemical studies of the historical and late Holocene period have not detected spatially broad and significant shifts in lithological character in muddy embayments in the central GBR (e.g. Cavanagh et al. (1999), Woolfe et al. (2000), Brunskill et al. (2002)). In part, detection is confounded by very high rates of biological mixing and dilution by pre-historic terrigenous shelf deposits. However, Brunskill et al. (2002) did document a few cores from mangrove tidal inlet mouths in the Herbert River region that had irregular variations of organic matter over the core sediment depth (typically <2 m), perhaps caused by mangrove peat deposits from wind or flood events.

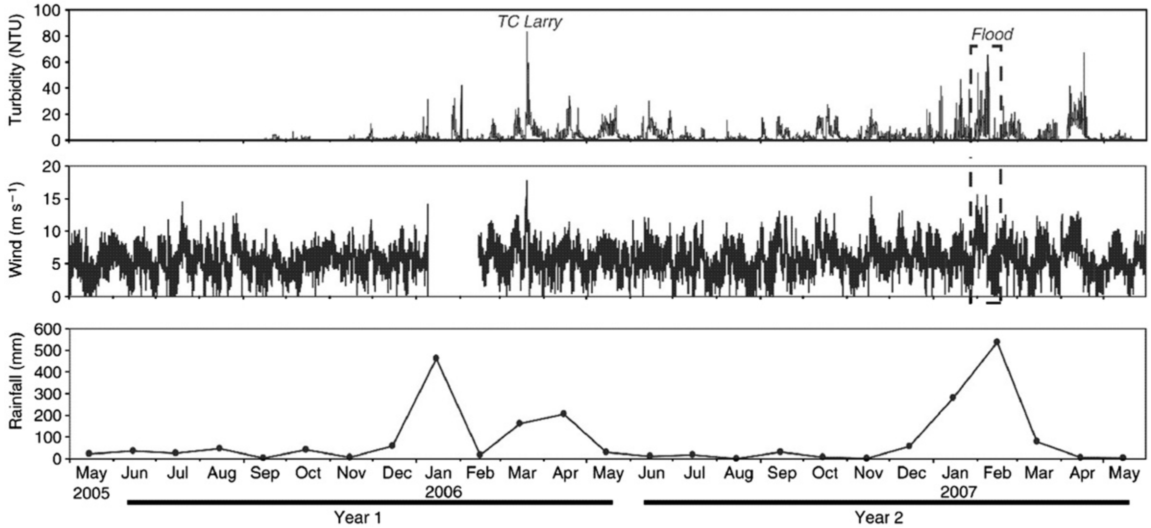

Fig. 2. (*top*) Turbidity (NTU), (*middle*) wind speed (m/s) and (*bottom*) total monthly rainfall (mm). Turbidity was recorded by a logger at a shallow depth (2 m below Lowest Astronomic Tide) on the fringing reef at Horseshoe Bay. Note that 1 NTU corresponds to between 1 and 2 mg/l (e.g. Devlin and Schaffelke (2009)) but is extremely particle size dependent. Wind was recorded by an automated weather station in Cleveland Bay. Gaps in the time series are due to instrument malfunction. The dashed lines denote the time series shown in Fig. 4. The heavy vertical line is on 12 Oct 2006 when the image in Fig. 3 (*bottom*) was taken. The figure is reproduced from Cooper et al. (2008).

The bedload component (sand) from sub-catchments within the largest dry-tropics watersheds show varying responses to localised rainfall events and land-use (Maher et al., 2009). However, similar provenance discrimination of the suspended fraction has not been attempted for terrestrial sources and marine sinks. Bioturbation, bed resuspension and mixing, and marine alteration of clays likely presents significant hurdles to discriminating spatial and temporal changes in suspended sediment character in the coastal zone. Nonetheless, century-scale lithological changes could well have occurred in sympathy with increases in catchment yields from climate or land-use change, as is inferred from complex delta-lobe construction in the Burdekin River over the Holocene (Fielding et al., 2006).

4.3. Disentangling flood and resuspension events in a dry-tropics system: case studies from Magnetic Island and Cleveland Bay proximal to the Burdekin River mouth

Cooper et al. (2008) present an 18 month dataset of water turbidity (Fig. 2) at Horseshoe Bay on north side of Magnetic Island around 12 km from the mainland coast, 100 km north west of the mouth of the Burdekin River (Fig. 1). These turbidity data capture a moderately sized flood (1 in 5-year event) from the Burdekin River, and a satellite picture taken on 10 February 2007 (day 41) indicates that Horseshoe Bay was enveloped by the river plume (Fig. 3; Cooper et al., 2008), consistent with long term observations of the location of the Burdekin flood plume by Devlin et al. (2001b). A sequence of turbidity events occur that exceed ca. 20 NTU, each roughly a week in duration and spaced approximately one month apart (Fig. 2). All of these events are synchronous with periods of high winds and were interpreted to be the result of wave resuspension, consistent with earlier hydrodynamic studies in Cleveland Bay (Larcombe et al., 1995). Peak turbidity (>50 mg/l) during the 18 months time series was associated with the passage of Tropical Cyclone Larry in March 2006, and a high wind event in February 2007, which also coincided with the recording of a flood plume from the Burdekin River. Another sustained period of high turbidity occurred in April 2007 during an extended period of high winds and wave energy.

Although the turbidity event in February 2007 was synchronous with sustained high winds (and wind-generated waves), the flood plume that enveloped the site presumably also contributed to the water quality (Fig. 3). The relative influence of wave resuspension and river plumes on the turbidity can be seen by re-plotting the turbidity data on a larger scale (Fig. 4). The turbidity event started on day 30 and peaked at over 50 NTU on day 32, coincident with the highest wind speed. Turbidity fluctuated considerably over the following 9 days, culminating in a large 65 NTU peak on day 39-40 (8-9 February 2007), after which the turbidity dropped rapidly with falling wind speeds. Significantly, a period of low turbidity that occurred on days 33 and 38 was coincident with relatively low wind speed.

Throughout this turbidity record the lack of coherence between river discharge and turbidity seems apparent (Fig. 5). Cooper et al. (2008) showed that there were sustained periods when very high turbidities occurred in the bay with almost zero river flow, such as January 2007 preceding the wet-season flood (Fig. 5). Flooding in the Burdekin commenced on day 33 (solid black arrow, Fig. 4), two days after the high turbidity event had started offshore. The Burdekin River also remained in flood for a week after the turbidity event ended on day 40 and the turbidity had subsided to background. These data demonstrate that flood stage height in the Burdekin River has little correlation with the turbidity recorded at Horseshoe Bay, even though this area is often enveloped by the turbid river plume.

A contrasting proposition to this quandary comes from an alternative Cleveland Bay study by Lambrechts et al. (2010), who implied that flood-derived suspended sediment has an overriding contribution to the long-term (sub-annual) mass balance for coastal turbidity, i.e. SSC *is* sediment-supply limited. Their modelling suggested that a four-fold reduction in riverine suspended sediment from the Ross and Burdekin rivers might halve the turbidity within Cleveland Bay within 170 days. They utilsed a 2D hydrodynamic model together with a simple parameterisation of sediment resuspension from waves to produce simulations of SSC at a number of reef locations in Cleveland Bay. SSCs of around 50 mg/l were observed during periods of high wave activity and peaked at over 200 mg/l at Geoffrey Bay, consistent with the data of Orpin et al. (2004b). In contrast, when Cleveland Bay was bathed in flood plume water from the Burdekin River the SSC was less than 10 mg/l. The conclusion that a reduction in riverine sediment discharge would halve SSC after 170 days following the

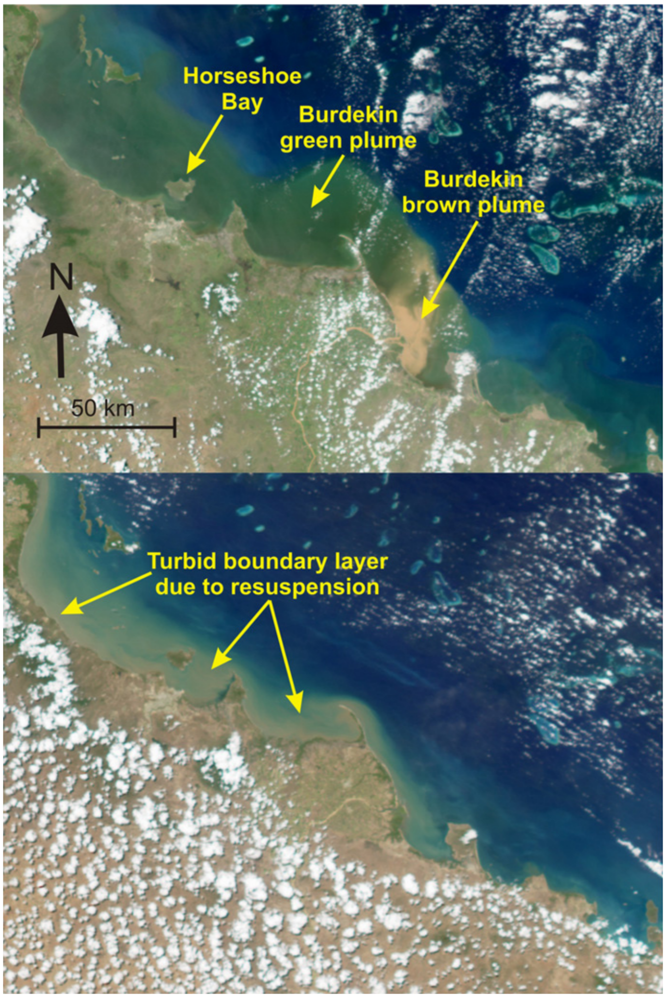

Fig. 3. (*top*) MODIS Aqua Image 10 February 2007. The flood plume from the Burdekin River can be clearly seen at the river mouth extending to the Palm Islands and well beyond to the north. The plume completely envelops Magnetic Island. The plume close to the river mouth is brown and becomes blue/green as distance increases from the mouth. The instrumental record at Horseshoe Bay shows low turbidity on this day (Fig. 2 and Fig. 4); (*bottom*) MODIS Aqua Image 12 October 2006. This image, taken during a strong wind event during the dry season, clearly shows the turbid coastal boundary layer which extends beyond Magnetic Island. The instrumental record at Horseshoe Bay shows high turbidity on this day (Fig. 2).

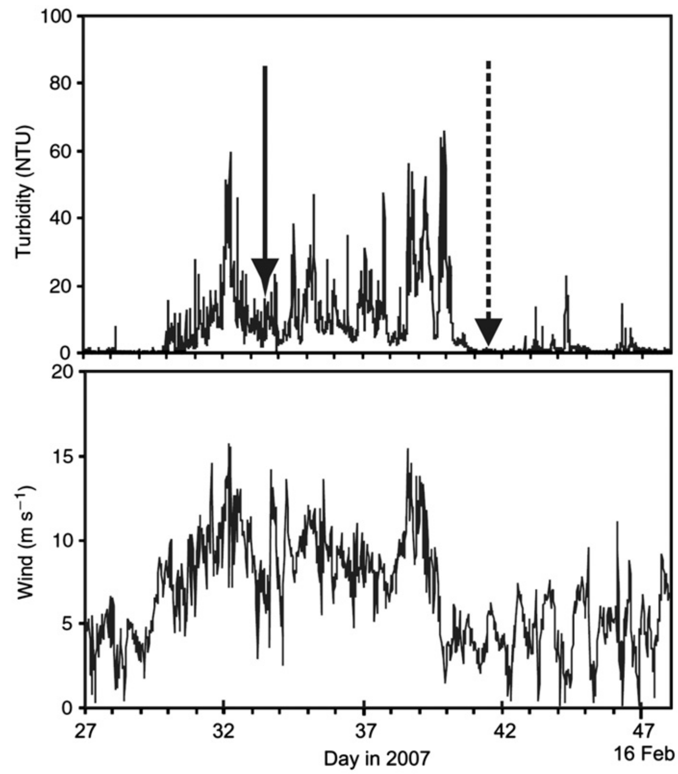

Fig. 4. Turbidity (NTU) and wind speed (m/s) recorded during the flood event in February 2007 (modified after Cooper et al. (2008)). The solid arrow indicates the commencement of major flooding in the Haughton River. A peak level of 3.8 m was recorded above the Burdekin Falls Dam spillway on 4 February 2007 (Bureau of Meteorology). The dashed arrow represents the time of the MODIS Aqua Image 10 February shown in Fig. 3 (*top*). Dates on time axis represent 00:00 hours on the date shown.

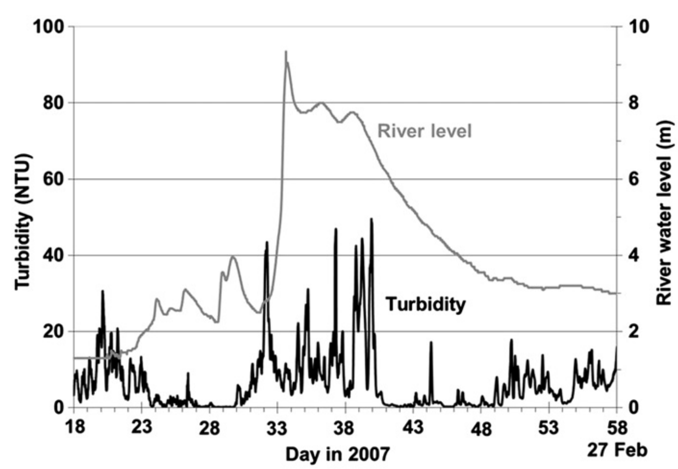

Fig. 5. Water turbidity at Horseshoe Bay from Cooper et al. (2008) plotted against the Burdekin River water level at Inkerman Bridge. At water levels less than ca. 1.3 m, the Burdekin River has effectively stopped flowing. Day in 2007 on the time axis represents 00:00 hours on the days shown.

cessation of floods was based upon the observations that three turbidity peaks (see Fig. 2a in Lambrechts et al., 2010) in the latter part of the year were not as high as predicted considering the wave conditions. Seasonal export of suspended sediment from shallow to deeper waters and bed armouring were inferred to be key processes for this reduction, however, the relevant wave data were not presented and thus it is difficult to critically explore the veracity of this finding any further.

4.4. Disentangling flood and resuspension events in a wet-tropics system: case studies proximal to the Tully River mouth

Wolanski et al. (2008) present SSC data from the inner and middle-shelf adjacent to the Tully River mouth and nearby fringing reefs, together with a suite of oceanographic parameters, including current velocity and wave height. They show a fortnight-long period in which a bi-modal, moderately sized flood event (90–100 m^3/s) occurred in the Tully River (Fig. 6). The flood was caused by a period of heavy rainfall ($>$ 60 mm per day) associated with monsoonal activity and strong southeast and southerly winds. Wave energy was sufficiently high (significant wave height $>$ 1 m) to cause non-tidal fluctuations in the tide gauge record around day 39 (Fig. 6). Longshore currents measured during the wind event were orientated northward and peaked at 1 m/s. During the flood the salinity at fringing reefs on the Family Islands reduced to around 30 ppt, with occasional short periods (few hours) freshening to 20 ppt. The SSC in the Tully River peaked on day 32 at 200 mg/l on the rising stage of the first flood

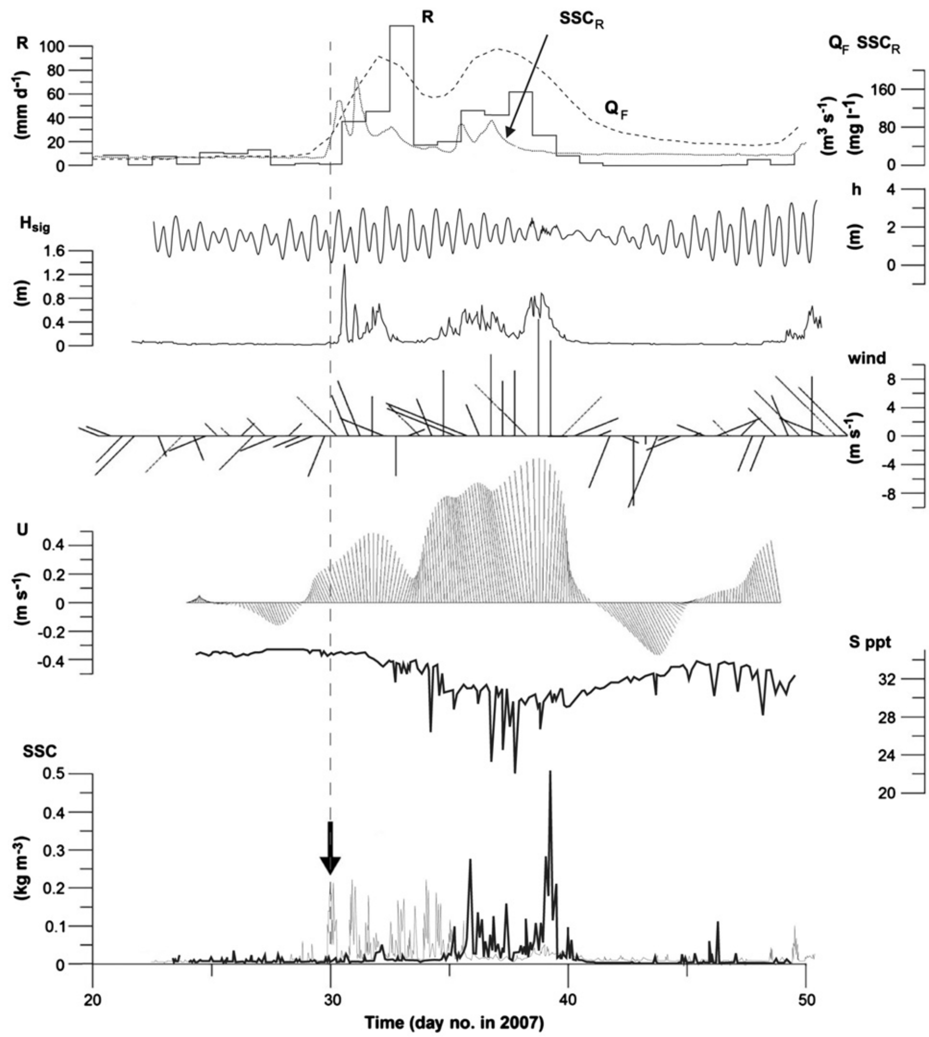

Fig. 6. Time series plots modified after Wolanski et al. (2008) of daily rainfall (R), Tully River freshwater discharge (Q_F), Tully River suspended sediment concentration at 1 m off the bottom (SSC_R), sea level (h), significant wave height (H_{sig}), wind vectors (shown using oceanographic convention), tidally averaged current vectors (u) at site D2, salinity (S) at sites B4, suspended sediment concentration (SSC) at 4 m depth at sites B4 (heavy line) and B5 (light line). Note that in Wolanski et al. (2008) the units for the river SSC are plotted in g/l but those for the coral reef sites are plotted in mg/l. The arrow points to the first SSC peak in the event discussed in the text.

peak in flow, with a pair of smaller peaks around 100 mg/l occurring around day 37 immediately preceding the second flood peak. Over this period, SSCs at the Family Island reef sites were highly variable, but the main periods of elevated SSC were coincident with periods of elevated wave height and high river discharge. However, Wolanski et al. (2008) interpret that the high turbidity event (labelled with an arrow, Fig. 6) occurred during low energy sea-states and can thus, categorically be attributed to the arrival of the river plume. They go on to conclude that ''the bulk of the sediment reached the coral reefs from the first flush of mud eroded from the river catchment during the rising stage of the river flood.''

As a null hypothesis, could it be argued that the ''flood'' peak (marked with the arrow in Fig. 6) was unrelated to the river plume? Four lines of evidence might indicate that the flood and offshore SSC peaks were not synchronous and directly coupled. Firstly, close inspection indicates that the arrow-marked SSC peak (Fig. 6) occurred one day before the initial peak in SSC in the river, when there should have been a considerable lag time for the plume to traverse the inner and middle shelf to the offshore fringing reefs of the Family Islands. Wolanski et al. (2008) indicated that the plume speed was 0.1 m/s, or ca. 10 km per day. Thus, for the SSC peak at the offshore reefs to be sourced from the flood plume, it should have occurred well after the ''first flush'', not simultaneous with it, and certainly not before. Secondly, the salinity measured during the marked SSC peak was only ca. 0.3 ppt below the background non-plume salinity, indicating that this water was comprised of ca. 1% riverine water and 99% seawater. Hence, by day 30, no significant plume had developed at Bedarra Island (sites B4 and B5) and the elevated SSC was unlikely to be related with the plume. Thirdly, the SSC of the marked peak is ca. 200 mg/l, compared with a lower value of ca. 120 mg/l in the Tully River. Considering that dilution with seawater (by 99%), flocculation and settling would occur as the plume entered inner-shelf waters, if SSC was driven primarily by riverine supply, a considerably lower concentration would be expected at site B5 some 10 km offshore. And fourthly, satellite data generally demonstrate the broad spatial extent of flood plumes along the coast (e.g. Fig. 3). Thus, if the peak at site B5 was caused by a river plume, it is surprising that a similar peak did not also occur at the other sites, especially at site B4 which was 2 km closer to the river mouth and inshore of site B5.

If the ''flood'' peak in SSC was not caused by a flood plume, then what is a likely alternative explanation? It is possible that it was a more localised effect driven by the building winds that eventually caused the elevated sea-states (Fig. 6). A wind change from a northerly at 5 m/s to southeasterly at 8 m/s was synchronous with the turbidity event in question. Although this direction swing did not immediately cause the high sea-states (swell waves did not develop for another 12 h), locally generated short-period waves can nonetheless resuspend unconsolidated material on nearby shoals and shallow coastlines (e.g. Larcombe et al., 1995).

First-order quantification of the relative sediment fluxes through the inner-shelf channel of this wet-topics example might resolve the likely mass balance of coastal versus riverine contributions over the time scale of the deployment. Although Wolanski et al. (2008) collected data across the channel, only SSCs from the more seaward site adjacent to Duck Island were presented, which may not be representative of the potentially more turbid conditions closer to the shore. Nonetheless, using the average persistent northward current of 0.8 m/s on day 34–39 over a cross-sectional area of the channel of ca. 30,000 m^2, and an SSC of ca. 0.05 kg/m^3 measured offshore, a conservative estimate of the sediment mass flux through the channel over these five days is perhaps 500,000 t. During the simultaneous discharge peak from the Tully River (day 30–39), the Tully discharged ca. 200 Mm^3 of water with an average concentration of 0.1 kg/m^3, equivalent to ca. 20,000 t of sediment. A useful focus for future work would be to more tightly constrain the estimate of longshore sediment transport using the SSC directly measured within the channel, and delineate any variability in the transport vectors over the longer timescale of the deployment.

Relatively low SSCs in flood waters from the Tully River are further supported by Devlin and Schaffelke (2009) who collected data over a series of events from 1994 to 2008. Data taken from logging instruments during floods in 2007 and 2008 averaged only 3 mg/l. The peak concentration measured via direct water sampling in the period 1994–2007 was 39 mg/l but dropped rapidly with increasing salinity from of the river mouth; at salinities <5 ppt the SSC averaged 20 mg/l, reducing to around 5 mg/l above 20 ppt salinity. These data reinforce that the SSC measured in the lagoon from wave-driven resuspension is often greater than the river SSC, even before dilution, flocculation and settling occurs in the offshore plume.

4.5. Pitfalls interpreting water quality from satellite imagery

Satellite images can give an unrepresentative impression of water turbidity. The satellite image on day 41 (10 February 2007) (Fig. 3) was taken a day after the cessation of the large turbidity event (>50 mg/l) in Cleveland Bay outlined in Cooper et al. (2008) (Fig. 4, dashed arrow), when measured water turbidity had dropped dramatically to background levels of only a few NTU. The water discolouration shown in the satellite image was not reflected in the instrumental record, but there are a range of possible explanations for this. Firstly, the turbidity sensor was located on the sea bed, several metres below the buoyant plume visible from above the sea surface. However, irradiance levels had recovered substantially by day 41 (Cooper et al., 2008) indicating that in fact relatively low turbidity water was above the light sensor. Secondly, the discolouration of the water in the plume was also caused by a range of scattering materials including phytoplankton, algae blooms, and dissolved organic molecules. Dissolved organic material may not be effectively measured by the turbidity sensor as the backscattering coefficients of this material may be much lower than for sediment.

The presence of a turbid coastal-boundary layer is a common feature and is frequently evident in satellite images of the GBR. For example, a dry-season image taken on 12 October 2006 (Fig. 3) showed a high turbidity event (20 NTU) at Horseshoe Bay during a period of elevated winds (10 m/s), when all nearby rivers had ceased flowing. It is evident that on this occasion, significant water discolouration extended from the coastline to approximately the 20 m isobath and enveloped Magnetic Island, and was similar in appearance to the image of the flood event on the 10 February 2007 (Fig. 3). But unlike the image of 10 February 2007, on 12 October 2006 the turbidity sensor showed a synchronous high in SSC.

Even though satellite images may give a limited impression of relative sediment concentrations, dispersal pathways of other dissolved and suspended materials, such as nutrients, pesticides or other adsorbed pollutants associated with flood plumes, the images may be usefully studied to provide other oceanographic data (Brodie et al., 2010).

5. Sediment dispersal lessons from other reef settings and continental shelves globally

At Hawaiian fringing reefs, fluvial loads contributed to high SSC for short periods, but were a minor contributor to annual budgets compared with wave driven resuspension (Storlazzi and Jaffe, 2008). Here, sediment trap collection rates correlated well with wave-current near-bed shear stresses during non-flood periods. Flood delivery of fine-grained sediment to the bay initially caused high turbidity and sedimentation off the river mouth but the plume dispersed quickly. Over the next month, the flood deposit was reworked by mild waves and currents and the fine-grained terrestrial sediment was advected around the bay's seabed with no surface plume. As such, Storlazzi and Jaffe (2008) suggest that these slow-moving, reworked flood deposits, potentially pose a greater long-term impact to benthic coral reef communities than the flood plumes themselves. Wave-driven re-working of shelf deposits (whether historic or ancient) can cause elevated turbidity and at least temporary sedimentation near the seabed where corals live, directly impacting them through temporary smothering or burial of recruitment sites (e.g. Storlazzi et al. (2009)). Such studies reinforce how spatial and temporal differences in hydrodynamic processes can cause substantial variations in the dispersal of both reef and fluvially derived sediment over relatively short spatial scales.

At Shiraho Reef that fringes the southeastern coast of Ishigaki Island (Japan), accumulation rate and turbidity measurements at the reef by Thomas and Ridd (2005) did not reveal any significant variations in sediment accumulation near coral colonies directly related to a high river discharge event or a typhoon event. Accumulation rate patterns and levels did not change significantly with higher waves, stronger currents, larger discharge, or more turbid water than average. They speculate that the main control of increased accumulation might be linked to tidally reduced water depths, which encouraged reworking of sediment by waves, even when small.

Other biochemical factors can affect the behaviour of particles in suspension and resuspension kinetics at reefs. In the southwest lagoon of New Caledonia in the tropical Western Pacific, Aymeric et al. (2008) found that within muddy coastal embayments and across the shelf, the highest percentage of aggregates contained within the total suspended particulate matter was proximal to barrier reef and coral islands. They suggest that at reefs, the abundance of exopolymeric substances may enhance the sticking properties of suspended particles, increasing the critical level of turbulence necessary to break aggregates apart. Such interactions have previously been suggested for turbid inner shelf and quiescent coastal waters from laboratory experiments (Fabricius and Wolanski, 2000; Fabricius et al., 2003). These studies reinforce that biological aggregation is an important process in suspended particle transport at coral reef environments, emphasising the need for a holistic approach to oceanographic studies.

In general, wave resuspension of bottom sediments, rather than flood plumes, has been found as the dominant process controlling gross cross-shelf sediment transport. For example, the very large, muddy and tide-dominated Fly River Delta immediately north of the northernmost GBR, only exports sediment to the adjacent shelf during the southeasterly trade-wind season (modulated by El Niño), when wave re-suspension processes produce hyperpycnal and gravity-supported density flows on the delta front and shelf clinoform (Harris et al., 2004; Ogston et al., 2008). Similarly, studies of the Eel River system on the coast of California showed that flood events are not a necessary condition to drive sediment escape to the upper slope Eel Canyon, but rather it is seasonal storm processes that govern the timing of sediment export off the shelf (Alexander and Simmoneau, 1999; Puig et al., 2003; Mullenbach et al., 2004; Traykovski et al., 2007). Moreover, on the Eel slope intermediate nepheloid layers were an important off-shelf pathway, accounting for more than 50% of the sediment mass accumulating on the seabed (Walsh and Nittrouer, 1999). Here, the flux was controlled by a combination of shelf sediment resuspension, river discharge, and margin circulation. Similarly, storm events and wave resuspension of shelf sediment also controlled the export to canyon heads in the Gulf of Lyons (Palanques et al., 2006).

These examples reinforce that terrigenous sediment dispersal and turbidity within the GBR is governed by physical processes common to many continental shelves, albeit that the wave climate on open shelves will be more energetic than within the reef lagoon. As such, any oceanographic appraisal that examines sediment dispersal within the lagoon must adequately constrain the temporal and spatial variability of these global drivers.

Perhaps the reoccurring theme raised by such studies is the challenge to calibrate the balance of low-frequency and high-impact events of short duration within a background of high-frequency and low amplitude processes. Such a problem only serves to reinforce the need for time-series measurements at meaningful length-scales to adequately measure physical and biological processes, and their variability. More high-quality observational data can only enhance our ability to disentangle potential behavioural shifts in environmental responses.

6. Future studies that address our current knowledge gaps

Despite the significant advances in our understanding of sediment transport and accumulation processes in the GBR, there remain many important gaps in our knowledge. Further data would add considerably to a more quantitative understanding of processes, fundamental to any critical assessment of causal linkages or environmental impacts. Some key themes that warrant further research include the following:

(i) Almost all instrumental data has been taken within 0.5 m from the sea-bed and thus any stratification in the water column has been largely overlooked or inferred. For example, significant stratification occurs in hypopycnal plumes, and also in rough weather when near-bed SSC are likely to be higher than at the sea surface.

(ii) Although there is now considerable SSC data for fringing reef systems, there are many reefs where there is effectively no hydrodynamic data. An appreciation of the sedimentological, ecological and geochemical gradients across and along the shelf might suggest that the most sensitive regions to change are those at the "feather edge" between marine and terrestrial influences (cf. Woolfe and Larcombe, 1999). Here, prolonged or more frequent exposure to significantly elevated turbidities could critically affect the energetics of benthic primary producers (cf. Anthony et al., 2004) and drive ecological shifts. To date, many studies have been limited to end-member environments: the coastal zone or blue water sites. Time-series measurements across the range of reef environments are needed, spanning the coastal fringing reefs to the outer-reef matrix, perhaps along transects adjacent to major rivers.

(iii) The pathways and magnitude of cross-shelf sediment fluxes are very poorly constrained at present. Tantalising and important insights were offered into shelf-wide dispersal by Wolanski and Spagnol (2000), but more data are needed before meaningful statements can be drawn about the temporal and three-dimensional spatial variability of shelf fluxes. More long-term measurements of SSC in deeper middle- and outer-shelf regions would provide a more holistic understanding of sediment dispersal across the continental margin and off-shelf sediment fluxes to the slope and Queensland Trough.

(iv) The role of frequency and magnitude in determining the impact or exposure of corals to elevated SSCs is poorly constrained by limited quantitative measurements during events, and the events themselves being placed into a broader temporal context. The logistics of sampling during storms or floods are considerable, but such data would be particularly useful to demonstrate causal links to physical, chemical and biological processes. Serviced environmental data stations might provide an alternative and have proven utility, e.g. Berkelmans et al. (2002).

(v) The primary deleterious effect of sediment on reefs is the reduction of light and smothering due to deposition (Fabricius and Wolanski, 2000; Fabricius et al., 2003). However, deposition is technically challenging to measure (Thomas and Ridd, 2004; Thomas and Ridd, 2005; Storlazzi et al., 2011), and the mechanisms and conditions for deposition of sediment on corals is poorly understood. Adding to the complexity of deposition is enhanced flocculation and particle adhesion caused by organic matter, as demonstrated in laboratory experiments (Fabricius and Wolanski, 2000).

7. Conclusions

Suspended sediment concentrations at fringing corals reefs around Magnetic Island and Cleveland Bay were strongly correlated to wave events that reoccur on time scales of a few weeks. The sediment-laden flood plumes from the Burdekin River envelop this area of the coastal zone for only a few days per year, and the impact directly attributable to individual floods is small and difficult to measure against the background SSC variability. Compared with wave resuspension, SSCs carried by river plumes are generally at least an order of magnitude lower at the reefs. Moreover, the annual exposure time of reefs to river plumes is also at least an order of magnitude shorter than for wave-resupension events. The net result is that river plumes likely have a relatively minor direct contribution to the mass balance of SSC events. Over inter-annual time-scales, perhaps the more compelling question is what time period might be required for the inner-shelf sedimentary system to become supply limited?

Satellite images of flood plumes can be a poor proxy for measured sediment loads, and as such should be interpreted with caution. River plumes are visually spectacular but most contain relatively low SSCs, which may cause decreased light penetration for a short duration (days), but are unlikely to directly impact the corals through smothering (causing them to expend energy during mucus production to slough off settled sediment), burying hard substrate and thus making sites for new recruitment unavailable, or other potentially deleterious impacts associated with sediment-borne pollutants.

Suspended sediment concentrations at fringing reefs around the Family Isles, adjacent to the mouth of the Tully River, were also strongly correlated to wave-driven resuspension events. Recent data indicates that the Tully River in flood largely carries low sediment concentrations (usually <30 mg/l) that are often lower than at the adjacent coastal zone and fringing reefs, particularly during periods of low flow and strong wind-generated waves. Furthermore, geological evidence indicates that many fringing reefs developed in highly turbid conditions at the coast; environments that have likely remained unchanged. Collectively, recent published data lends further support for the hypothesis first explored by Woolfe and Larcombe (1998) that sediment concentrations around many inshore reefs have not increased significantly since European settlement because wave-driven resuspension of muddy bottom sediments is the dominant control of SSC. Over geological timescales, at least the muddy inner shelf of the central Great Barrier Reef is likely not sediment-supply limited.

Terrigenous sediment dispersal and turbidity within the GBR is governed by physical processes common to many continental shelves globally. Despite the few examples detailed herein, the role of frequency, magnitude and duration in determining the impact or exposure of corals to elevated SSCs is poorly constrained by limited quantitative measurements during events, and our ability to place these into a broader temporal context. More high-quality observational data, at meaningful length-scales, can only enhance our ability to disentangle potential behavioural shifts in environmental responses.

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